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STUDY AND ANALYSIS OF THE FAITUGE FAILURE (OF BOLT ADAPTER) OF PROSTHETIC SACH FOOT

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ABSTRACT

In this paper, the study and analysis of failure mechanism of non-articular prosthetic foot (SACH) in the region (Bolt Adapter), the tests of mechanical properties and fatigue behavior were carried for material from which the bolt is manufactured, a region where the failure occurs and also analysis of the gait cycle and GRF of amputee subject and Compare it with normal subject and inserted of these properties to the program of engineering analysis (Ansys) to calculate the safety factor of fatigue and stress equivalent (Von-Mises) and lastly, the fatigue test to SACH foot is carried by Fatigue tester device to calculate the number of cycles to failure and to improving the fatigue properties to bolt the laser peeing was used to the material the bolt manufacture from it and testing the specimen after hardened and calculate the safety factor.The results showed that the safety factor after hardening by laser is increased by 42.8%.

In this paper, study the mechanism of failure in bolt of prosthetic and find the distribution of von- mises stress in foot and safety factor of fatigue and determine the number of cycles to failure at bolt and improving the fatigue properties of bolt material by laser peening and calculate the safety factor after hardened.

KEYWORDS: Analysis, Prosthetic, Foot, SACH, Fatigue, Bolt, Adapter

INTRODUCTION

The failure of SACH foot in bolt phenomena occurs due to effect of weight of person that variable during the gait cycle causing alternating stress in the weakest region of the SACH footis a screw.

The human ankle joint is a unique design that makes the joint stable and is capable of withstanding 1.5 times the body weights during normal ambulation and eight times the body weight during running, but the prosthetic SACH foot is incapable of withstanding 1.5 times the body weights during normal ambulation for long time because accrue the fatigue failure at ankle joint due to alternative loading.**[1]**

In the development of prostheses, allprosthetic assemblies and components aresubjected to structural acceptance tests whichinclude static and fatigue tests. Static tests arerequired to determine the structural strength ofthe foot to ensure performance and safety.These are carried out on a universal testingmachine. While this is important, fatigue teststo reveal the fatigue strength of the componentsmust also be performed. Fatigue tests aredesigned to study performance under load forthe equivalent of the expected service lifeduring normal use **[2]**.

The aim of the current work is to analysis the fatigue failure of the bolt adapter used in SACH foot. To achieve the above objective, the numerical analysis by using ANSYS program to find the safety factor and the equivalent Von-Mises stress of SACH foot at gait cycle and the experimental work by Calculating the life of SACH foot by using fatigue foot tester device and measuring the mechanical and fatigue properties of bolt material.

From the above, the following design parameters may be obtained:

- Testing the material of bolt to measure the mechanical and fatigue properties.
- Measuring the safety factor and the equivalent Von-Mises stress of SACH foot at gait cycle.
- Study and analysis the mechanism of failure in SACH foot at bolt adapter.
- Improving the fatigue properties of bolt material by laser peening and comparing the performance of LP with dry fatigue.
- Calculating the life of SACH foot by using fatigue foot tester device.

FAILURE ANALYSIS

The failure occurs as a result of load that be in heel and toe of foot in intermittent periods and regular during the phases of gait and that lead to alternating moment and opposite directions about the point A .Where at heel strike phase as shown in figure 1 the ground reaction force applied on the heel of the foot upward vertically and the axis of the foot is italic so that the force analyze to two components, the first parallel to the axis of the screw and its operating moment in clockwise about the point A in distance L_1 and the second perpendicular to the axis of the screw and its operating share stress and its small amount so its neglected, while at toe off phase as shown in figure 2 which be vertical upward to the foot and analyze to two components, the first parallel to the axis of the screw and its operating moment in anticlockwise about the point A in distance L_2 and the second operating share stress and its small amount so its neglected too. From figure 1 and 2 noted that the L_2 larger than L_1 so that the moment in toe off phase larger than the moment in heel strike phase.

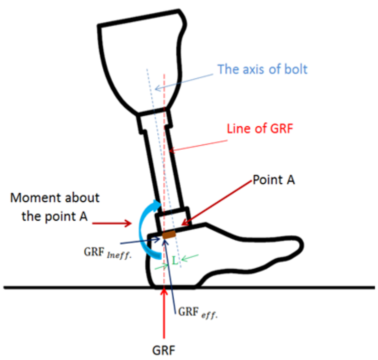

Figure 1: GRF at Heel Strike Phase

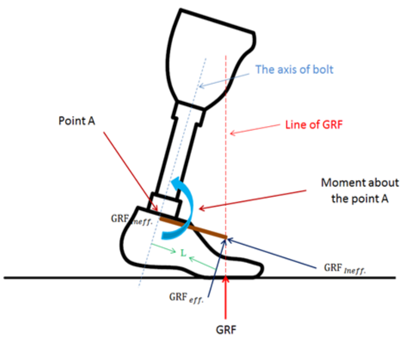

Figure 2: GRF at Toe off Phase

MODELING THE SACH FOOT BY AUTOCAD

In order to conduct the finite element analysis, all of the components needed to be modeled. All of the components to be tested were modeled in Pro/AutoCAD 2011.

FINITE ELEMENT ANALYSIS BY ANSYS

ANSYS Workbench was chosen as the FEA software package because of its ability to accept a 3D computer aided design (CAD) model and assembly of high complexity. The program also allows for the accurate placement of angled pressures and loads, in addition to the modeling of contact surfaces and large deflection.

In the modeling of SACH foot, the standard tetrahedral elements were used because the elements have plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. The automatic size control was used to mesh the model as shown in figure 3, with refined meshing at the notches of the bolt.

The total number of elements was (46889 elements) with total a number of nodes of (81263 nodes.).

Applied the same boundary conditions (constraints and loads) that taken from the GRF test. The tip of the adapter was selected as fixed support for the four sides at all time. a vertical upward pressure of 310 Kpa was applied to the bottom surface of the heel from 0% to 21% of gait cycle and 310 was applied to the bottom surface of the toes from 69% to 100% of gait cycle as shown in figure 4.

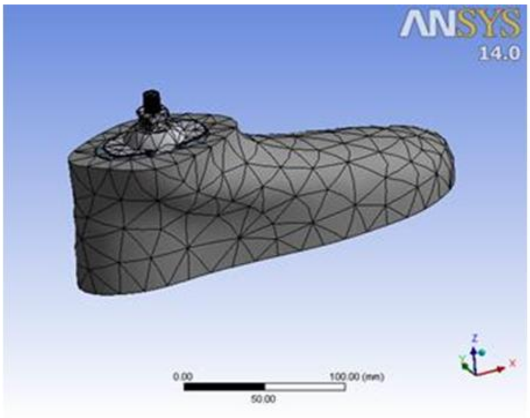

Figure 3: Meshed SACH Foot Models

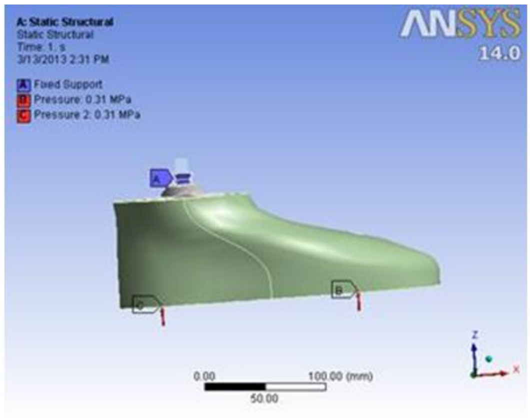

Figure 4: FEA Model Constraints and Loads

EXPERIMENTAL ANALYSIS

Mechanical Properties

The tensile test was done by using the tensile test machine the tensile specimen's geometry and dimensions knew by using standard (A370)**[3]** which was specified for metals (Stainless steel).

The Fatigue Test

A fatigue–testing machine that applied a rotating bending that used to execute all fatigue tests, with constant and variable amplitude. The specimen is subjected to an applied load from the right side of the perpendicular to the axis of specimen, developing a bending moment .Therefore; the surface of the specimen is under tension and compression stress when it rotates.

Laser Peening

The laser peening test was carried out at (AL- technologieh University) by using (Q-switched neodymium –YAG laser) that has the following parameters:

- Laser wavelength is about 1.065 µm.
- Pulse duration 7 Nano seconds.
- Pulse energy 300 mJ.
- The laser spot is typically (4-7) mm in diameter.
- The deep water to the area that treated is typically (5-10) mm.

The selection 300 mJ of plus energy of laser peening because this gave best fatigue characteristic **[1]**.

Figure 5 shows (Q-switched neodymium –YAG laser system) used in the following work.

The specimens are coated by using the dark paint as shown in figure 6.

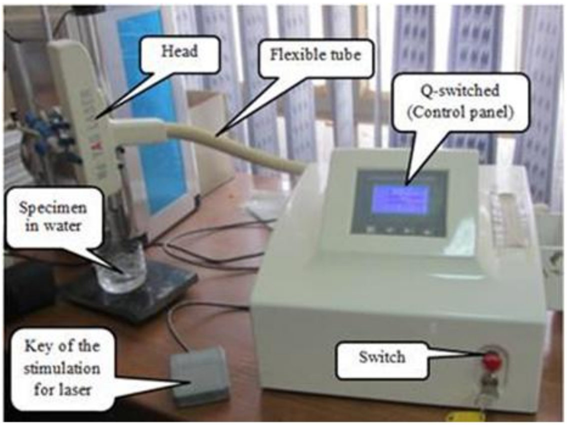

Figure 5: The Fatigue Specimens Test after Coating

Figure 6: Details of Laser Peening Test Rig in University of Technology (Laser and Electroptical Engineering Department)

Fatigue Foot Test

The SACH foot is placed on the fatigue tester in order to obtain the life of the foot. The fatigue tester simulate human gait by alternating the heel and toe loadings. The load is alternative in order to simulate normal gait, the piston 1 struck heel foot and piston 2 struck forefoot in sequence. A counter in the fatigue foot tester recorded the number of strike. The frequency of strike was controlled by using the frequency meter according to The International Organization for Standardization (ISO Standard 10328) which outlines the test methods using static and cyclic strength tests. The static tests relate to the maximum loads generated, whereas the cyclic tests relate to normal walking activities.

The fatigue foot tester, Figure 7, was designed and built using the functional requirements outlined in ISO standards. According to ISO 10328 standards, forces must be applied at 15^o and anterior to tibia axis upon heel strike and $20\ ^o$ posterior to the tibia axis upon toe off, also CyclingFrequency must be1Hz **[4].**The specimen used in the fatigue foot test is machined from bolt that use in SACH foot to a suitable geometry for the testing as shown in Figure. 8.

Figure 7: Fatigue Foot Tester

Figure 8: The Fatigue Tester Specimen

RESULTS AND DISCUSSIONS

Fatigue Results

Fatigue failure occurs when the specimen fractures under cyclic loading. The readings recorded by the fatigue tester represent the number of cycles when the specimens fractured. The fatigue results are presented in the forms of curves. The fatigue test carried to 18 specimens without laser peening and 9 specimens with laser peening where the specimens hardened by laser. The figure 9 shows the S-N curves of results.

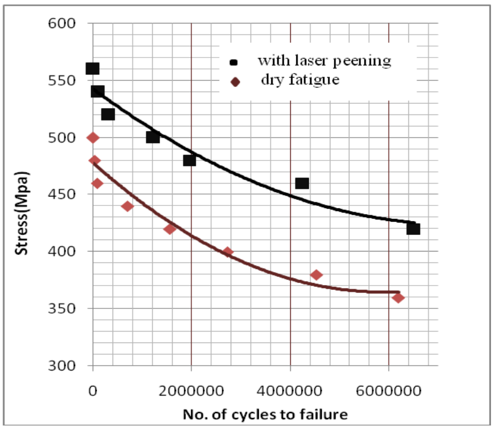

Figure 9: Comparison between the Fatigue Behavior with Laser Peening and without Laser Peening

THE RESULTS AND DISCUSSIONS OF THE GAIT CYCLE TEST

Vertical force is the ground reaction force in the vertical direction as measured by the force plate. The magnitude of vertical force is typically measured in newton. Vertical force is graphically represented by two peaks separated by a valley. The first peak occurs as a result of the initial impact of the foot on the ground. In the past, the second peak has been thought to represent a push-off by the ankle plantar flexors (posterior calf muscles).

The Result of the Numerical Analysis and Discussion

The fatigue and static properties of prosthetic SACH foot investigated using finite element method (ANSYS 14).

Static Analysis

The aim of this analysis is to investigate the stresses and safety factor of SACHfoot at maximum pressure that taken from ground reaction force.

Figures 10 &11 show the distribution of Von-Mises stresses in the prosthetic SACH foot at toe off phase and heel strike phase, respectively, it is clear that amaximum stress is appear located in bolt at interface regain between adapter and foot at notch because the cross section is minimum at notch. Where observe the maximum Von-mises stress is at the toe off phase not at the heel strike phase because of the normal distance at the toe off phase more than at the heel strike phase, that make the maximum stress at the toe off phase.

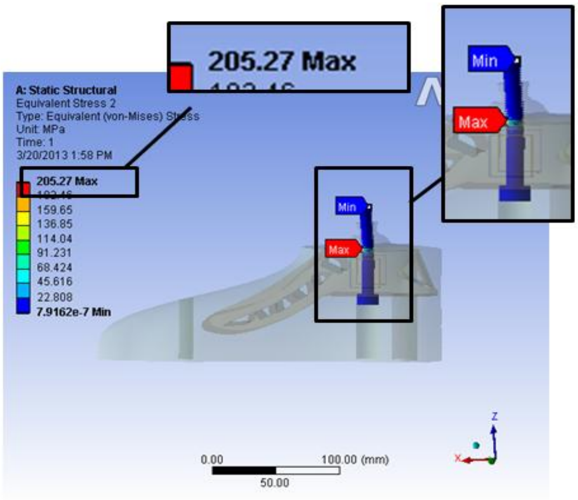

Figure 10: Von-Mises Stress of Prosthetic SACH Foot (Heel Strike Phase)

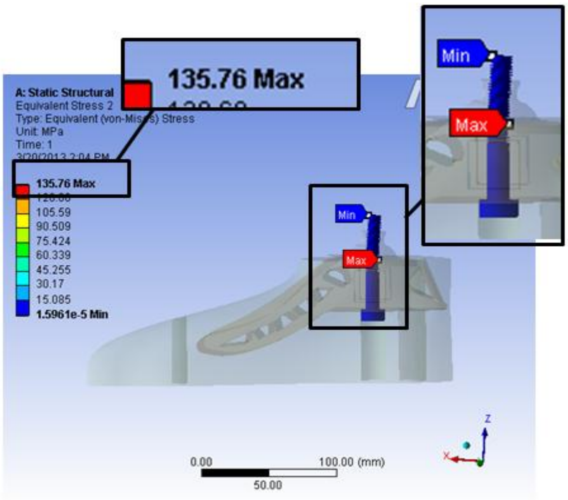

Figure 11: Von-Mises Stress of Prosthetic SACH Foot (Toe off Phase)

Figures 12 & 13 show the equivalent stress-safety factor for the prosthetic SACH foot. It can be seen from the figure that the maximum equivalent stress-safety factor is located in bolt at interface regain between adapter and foot at notch because the cross section is minimum at notch, and the equivalent stress-safety factor at toe off phase less than at heel strike phase because of the maximum Von-Misses stress at toe off phase more than at heel strike phase.

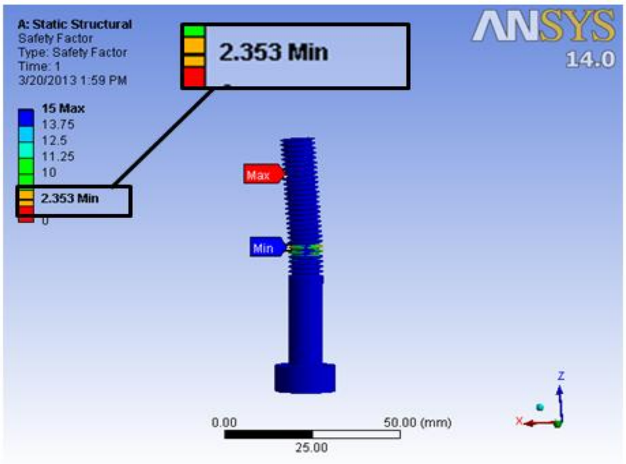

Figure 12: The Equivalent Stress-Safety Factor of the Prosthetic SACH Foot for Static Load (Toe off Phase)

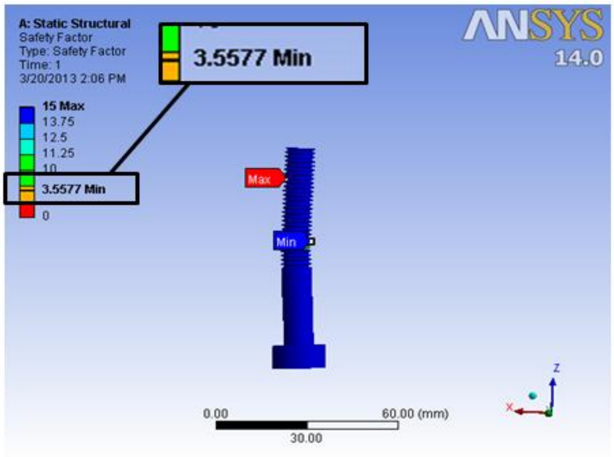

Figure 13: The Equivalent Stress-Safety Factor of the Prosthetic SACH Foot for Static Load (Heel Strike Phase)

FATIGUE ANALYSIS

The aim of this analysis is to investigate the equivalent (Von-Mises) stress and safety factor of fatigue of prosthetic SACHfoot.

According to the Von-Mises theory that considers the yield stress as criteria; ($\sigma_e<\sigma_y$, safe), ($\sigma_e = \sigma_y$, critical) and ($\sigma_e>\sigma_y$, failed).

Where, (σ_e) is the equivalent stress, and (σ_y) is the yield stress.

The safety factor for fatigue will be safe in design if the safety factor about or more than (1.25) **[5]**.

Figure 14 shows the equivalent stress-safety factor for the prosthetic SACHfoot without using laser peening. It can be seen from the figure that the minimum equivalent stress-safety factor is located in bolt at interface regain between adapter and foot at notch because the cross section is minimum at notch.

Where observe the minimum equivalent stress-safety factor is at the toe off phase not at the heel strike phase because of the normal distance at the toe off phase more than at the heel strike phase, that make the minimum equivalent stress-safety factor at the toe off phase and this make the crack initiation at the side of heel first and the failure initiation at this side.

To improve the fatigue properties of metals the laser peening (LP) is a surface enhancement technique that has been applied. The ability to use a high energy laser pulse to generate shock waves, inducing a compressive residual stress field in metallic materials **[6]**.

Figure 15 shows the equivalent stress-safety factor for the prosthetic SACHfoot. From noted that the safety factor of fatigue after laser peening increased by 42.8% as shown in figure 16 and this increment due to formed layer of compressive residual stress which inhibits both crack initiation and propagation this lead to life longer of bolt and more safety factor.

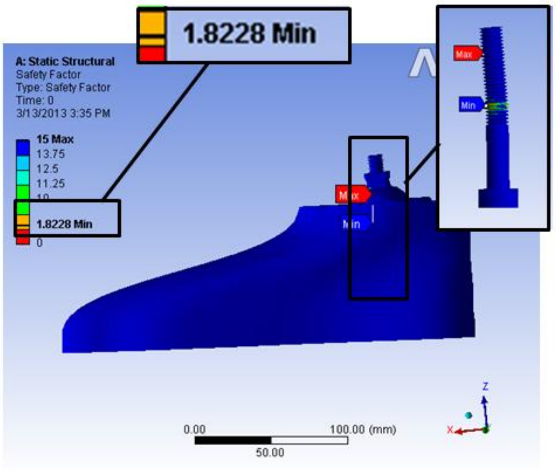

Figure 14: The Equivalent Stress-Safety Factor for the Prosthetic SACH Foot without Laser Peening

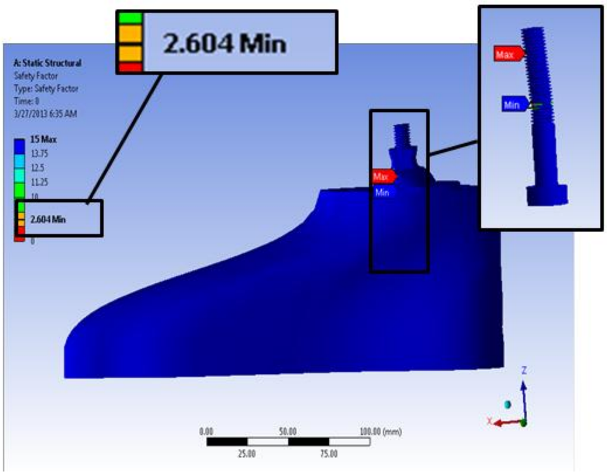

Figure 15: The Equivalent Stress-Safety Factor for the Prosthetic SACH Foot with Laser Peening

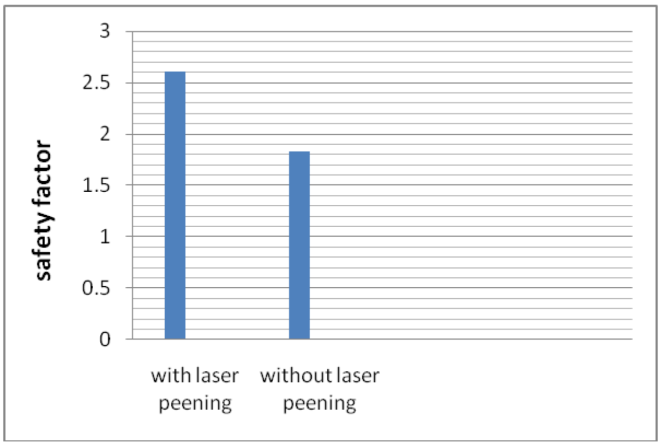

Figure 16: Comparison between the Safety Factor for Fatigue with Laser Peening and without Laser Peening

RESULTS AND DISCUSSIONS OF FATIGUE FOOT TEST

The current configuration of the fatigue tester is such that it applies a known force using two pneumatic cylinders, one at heel and the other at toe, to simulate walking with a prosthetic foot. The main problem with this concept is that force is not applied during the whole stepping process. But rather is applied at the two extremes of the cycle. By concentrating the ground reaction force to two locations, artificial wear regions are created at the point of application of the heel and toe cylinder.

The failure of prosthetic SACH foot occurred at 839000 cycles, as shown in Figure 17.

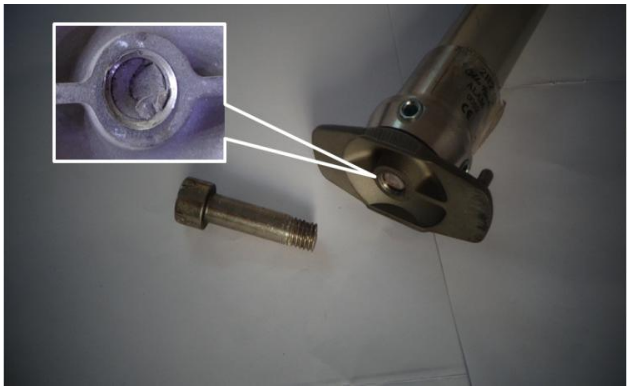

Figure 17: The Failure in Bolt after Fatigue Test in Fatigue Tester

CONCLUSIONS

- The fatigue safety factor is increase by 42.8%in bolt after laser peeing
- At static, the effect of the effect ground reaction force at toe off phase more than heel strike phase due to the perpendicular distance at toe phase lager than at heel strike phase
- The maximum equivalent Von-Mises stress is appear located in bolt at interface regain between adapter and foot at notch because the cross section is minimum at notch.
- The minimum safety factor is located in bolt at interface regain between adapter and foot at notch because the cross section is minimum at notch.

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